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USE OF MAN-MODELLING CAD SYSTEMS BY THE ERGONOMIST

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ABSTRACT

This paper discusses man-modelling CAD systems, focusing on their applications to ergonomics and the quality of their interface with ergonomists as users. Three specific systems are examined to demonstrate the applications and limitations of computer man-models that are presently available, and requirements for an ideal system are identified. Recommendations are made for future development of man-modelling CAD systems, and their presentation to the user.

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1. INTRODUCTION

Ergonomics is concerned with the relationship between man and his work, equipment and environment. To this end, ergonomists employ the principles of anthropometry, physiology and psychology to design or evaluate man-machine systems. But frequently their evaluations are done after the basic design parameters have been fixed. Hence, ergonomists must often suggest difficult or expensive modifications, or make rapid decisions based on subjective assessments and past experience. Therefore, design tools are required that make their contributions more timely and thorough. One such tool may be computer-aided design (CAD). However, there are two issues of particular concern to ergonomists regarding the use of this technology; i) how can CAD be used as an ergonomics assessment tool in the design process, and ii) what are the requirements to ensure that CAD software interacts well with the ergonomist as a user? These issues are addressed in the following discussion.

2. THE USE OF CAD AS AN ERGONOMICS TOOL

In workplace design, ergonomists act to minimise design-imposed stresses on the user by addressing reach, vision and body clearance issues. In part, they accomplish this through careful consideration of anthropometry and the principles of proper posture. Anthropometry is the application of scientific physical measurement methods to human subjects. Its data types include linear dimensions (e.g. heights, lengths, widths, perimeters), volumes and areas (both segmental and whole-body) and x-y-z coordinate listings. The uses of anthropometry are somewhat limited, however, since individual anthropometric parameters do not convey the relative position of man in space.

Anthropometry is fundamental to the manual analytical tools (i.e. mock-ups, anthropometric dummies, partial manikins, stick figure manikins, 2-dimensional drawing board manikins and manufacturers drawings) and established data bases that are used to provide crucial workplace design specifications. However, these analytical tools are limited in their abilities to adequately represent the user population, in the timeliness with which they can respond to design developments, and in the speed with which they can be reiterated as the design evolves.

With the widespread use of computers, techniques have been devised to produce design layouts, detailed engineering drawings and representations of assembly systems, effectively reducing some of the time-consuming tasks of the system and equipment designer [1]. There are, however, comparatively few computer programs which represent the human component of the man-machine system [2, 3]. This may be due to the complexity of the human body's shape, joint articulations and motions. To model these characteristics requires valid mathematical models of human movement, knowledge of kinesiology, anthropometry and biomechanics, and an understanding of complex computer graphics techniques [4].

The published literature suggests that existing CAD programs that model man address three distinct concerns: animation, biodynamics and anthropometry. Animated man-models generate goal-oriented human motion sequences that are unaffected by the environment. Biodynamic man-models reflect the effects of internal and external forces on the body. Anthropometric man-models represent various body sizes, proportions and joint-articulations. Most of the available systems have been developed by or under contract to government agencies and are not commercially available. Although there are several CAD packages employed for military applications [5], and it appears that there has been little development of man-modelling CAD programs in industry. Those programs that have been developed focus primarily on automotive and aerospace problems [6].

2.1. CAD Programs for General Workplace Applications

To evaluate the compatibility of a workplace design with potential operators, the desirable features of a CAD program include anthropometric man-modelling and workplace-modelling, with the capabilities to analyse reach, body clearance and vision. The advantages of using such a program are many. The method is fast, reliable, accurate, efficient and requires only one investigator: it facilitates decision making by giving the user fast feedback of results and minimizing his reliance on memory [7]. It is appropriate for assessments that are highly standardised, as in automotive and aerospace industries, with the advantage of easy comparison to standard design specifications. Depending upon the CAD program employed, analyses can be performed on pre-selected populations, fabricated population samples or individuals. The data, which are in computer storage, can be analysed and presented, graphically or numerically, at a location remote from the actual design site. Improvements or updates to the CAD program can be incorporated without the loss of continuity on program applications.

Man-modelling CAD can be used to generate a random sample of representative operators from population data by using Monte Carlo techniques. This approach was validated for the program CAR, where computer-generated reach envelopes closely matched anthropometric survey data [8]. Internal data checks, such as those offered by the program COMBIMAN [9], can be used to test the validity of the man-model by comparing the sum of computer-generated internal link-segments with expected external anthropometric dimensions. That way, the representation of specified anthropometric characteristics by the man-model is assured. In fact, computer-generated operator samples may be preferable to live subjects since far more anthropometric combinations can be assessed and known population differences can be reflected by editing the program algorithms.

Computer modelling is not without disadvantages. The software programs are expensive and customarily require the input of detailed workplace and anthropometric data, which can be laborious and time consuming to acquire. Since all models are defined mathematically, and replicate key input data exactly, it is important that valid data and transformation equations be employed. Most importantly, the limitations of the selected man-modelling program must be known: the user must understand the models' characteristics and how they influence the analysis of operator/workplace interaction.

2.2. Anthropometric Man-Modelling CAD Programs

Dooley [10] identified several anthropometric man-modelling CAD programs including: BOEMAN - for in-house cockpit design, developed for Boeing Corporation; BUBBLEMAN - a technique to visualize man, developed at the University of Pennsylvania; BUFORD - for in-house cockpit design, developed by Rockwell International; CAR - for aircrew reach assessment in the cockpit, developed by Analytics for the US Naval Air Development Centre; COMBIMAN - for the design of aircraft cockpit interiors, developed by the University of Dayton Research Institute for the US Air Force Aerospace Medical Research Laboratory; CYBERMAN - for automotive interior design, developed by Chrysler Corporation; and SAMMIE - for the evaluation of man-machine systems, developed by Nottingham University and available commercially from Prime Computer Ltd. Of these CAD systems, it is apparent that BUBBLEMAN, CAR, COMBIMAN and SAMMIE are currently under development and becoming increasingly sophisticated and reliable [9, 11-13] The details of some programs have remained inaccessible to the general user (e.g. BUFORD, CAR, COMBIMAN and CYBERMAN), and SAMMIE is the only program that is commercially available.

Other man-models are being developed. A man-model referred to as ERGOMAN has been reported [14], but no information was given as to its availability. Lockheed Missiles and Space Co. has developed ADAM (Anthropometric Design Aid Mannequin)

and EVE (Ergonomic Value Estimator), two man-modelling CAD/CAM programs to be used for considering human access, reach and working postures. No details are available on the features of these programs, which are not currently for sale [15].

2.3. CAD Programs for Aerospace Applications

The CAD programs CAR, COMBIMAN and SAMMIE have been assessed for their appropriateness as a primary workplace evaluation tool to assess aircrew/cockpit compatibility [16]. Since they represent a good cross-section of the features that are currently available for aerospace workplace applications, their general descriptions follow.

CAR:

Crewstation Assessment of Reach (CAR) was developed as a simple and inexpensive means to estimate the percentage of a given aircrew population that is physically accommodated by a given aircraft crew station [17]. The most recent version, CAR-IV, became available in 1984.

To use CAR, the investigator defines an aircrew sample and specific crew station parameters. The aircrew anthropometric data are taken from actual surface anthropometric measurements, or are generated from existing population data using a Monte Carlo correlation process [17]. The data must deviate less than ± 3 standard deviations from the means of a control set of data (i.e. US Navy data, 1964) and so cannot be radically different from the control population. Accepted input data are transformed into link segments, reference links and reference points, to represent the human skeletal structure. The crew station is defined by an anchorage point, the design eye point, seat characteristics, head clearance specifications and hand or foot control positions [17]. The anchorage point is used to position the aircrew to a fixed spot in the crew station while specifications for the seat, head clearance and controls outline the conditions under which the man-model is to perform.

The analyses performed include: ability to reach controls, ability to be positioned to the design eye point along the line of sight, ability to be positioned to a specified anchor, and head clearance to the aircraft canopy. Reach assessments can be completed for up to 50 controls, where each reach is effected by specifying the body part used, type of grip, harness restraint and harness location [17]. Where appropriate, the adjustment range of a control can be represented by two discrete points. CAR has no graphical capabilities, so illustrations cannot be produced for visual inspection. The program is intended for interactive use, but will accept data from card-image files. It is not well suited for assessments other than for reach in aircraft crew stations.

COMBIMAN:

Computerized Biomechanical Man-Model (COMBIMAN) was developed as an engineering tool to assist in the design and analysis of aircraft crew stations. The most recent update (Version 6) became effective in May, 1981.

To use COMBIMAN, the investigator must construct a man-model and crew station. The man-model is composed of link segments, reference links and reference points that are derived from 12 anthropometric surface dimensions [9]. The links can be varied by length, to reflect different proportions and percentiles, and by angular orientation. The man-model is generated internally, in three stages: the link system is generated from an anthropometric data source, ellipsoids are generated to represent enfleshment, and the ellipsoids are connected with tangential lines to define contours. Joint-movement restrictions are automatically imposed on the model. The crew station model is composed of up to 250 panels and 150 controls that can be entered to a data file or specified interactively at the keyboard [9].

To evaluate the man-model in the crew station, the man-model can be varied by proportion and position. A reach algorithm can be employed, using default seated postures (i.e. erect and slumped), to simulate reaches according to programmed movement patterns and limitations. Alternatively, the user can position each limb-segment independently, according to his own movement criteria. The 3-dimensional model can be viewed from any position about 3 orthogonal planes or from the position of the man-model's eye. The coordinates of any location in the modelled environment can be readily identified with reference to the (x,y,z) origin of the crew station. COMBIMAN was developed for crew station applications, however it is possible to model any work space that requires that the operator be seated. The application of the model is limited largely to vision plots and the evaluation of hand reaches to controls.

SAMMIE:

System for Aiding Man-Machine Interaction Evaluation (SAMMIE) was developed as an ergonomics tool for designers and engineers and became commercially available in North America in 1984.

The man-model is composed of link segments and reference points that are derived either from anthropometric surface dimensions or internal body-segment lengths. Enfleshment is achieved using cross-sectional (x,y) data for each of the model's body segments. Movement of the individual links is under the control of "comfortable" and "maximum" joint constraint data which may be changed to simulate different effects (e.g. normal human postures, restrictive clothing). The man-model may be varied according to whole body percentile, specified limb lengths and somatotype [13]. Although the anthropometric data source used to generate the man-model is determined by the SAMMIE user, a library of international populations has been prepared for use in SAMMIE.

The workplace-model components are defined 3-dimensionally, as primitive shapes (e.g. prisms, cuboids and cylinders) or by irregular solids (described by vertices, edges and faces). Their spatial and hierarchal relationships are specified to establish their orientation in the environment. The logical relationships among components enable mechanical functions to be simulated (e.g. raising of a seat through its range of height adjustment). Movements of workplace components may be logically grouped (e.g. table movement includes all items located on the table surface), or occur independently. The models can be generated interactively while using SAMMIE, or entered directly to a data file following off-line preparation [13].

Several features distinguish the SAMMIE program from other man-modelling programs: the capability to model general equipment-workplace complexes, the display options provided (i.e. mirror reflections, simultaneous displays of different views and a mesh-grid reference system), and reach and sight paths for sequential reference to a specified series of points. Two other features enhance the realism of the workplace model: structured sequences simulate the movement of equipment, and simultaneous display of multiple numbers of operators reflect the physical interactions of several people in the workplace. These features facilitate workplace assessment by taking advantage of man's ability to process large amounts of data when presented visually. SAMMIE is sufficiently general, yet sophisticated enough to be employed in robotics, transportation, materials handling, consumer product, building layout and military design applications [3].

3. THE INTERFACE OF CAD AND THE ERGONOMIST

The critical elements for successful design of CAD software to be used for workplace design are: general applicability, flexibility and ease of use. This is simply because

ergonomists, as users, bring varying skills, strategies and considerations to the design table, requiring the availability of different modelling and assessment methods. Based on the review of existing CAD software, the requirements of a preferred (ficticious) CAD man-modelling system have been developed. They are described here to suggest the variety of software features that are desirable for general workplace design applications. By implication, the more numerous the methods of modelling and assessing 3-dimensional designs, the more desirable is the system.

3.1. Man-Model and Workplace Representations

The ideal CAD man-model offers 3-dimensional representations of male and female populations that are either derived from an anthropometric data base or generated by the user. All major body joints and segments are represented, and in variable ways (e.g. by length, depth, breadth, circumference, mass, volume, somatotype) whereby different types of joints (e.g. hinge, ball and socket) can be assigned maximum and comfort movement constraints. The representation of man's vision, which has default characteristics that can be changed by the user, has comfort and maximum limits that are dependent upon visual arcs and eye rotations. Clothing and personal equipment can be modelled by manipulating body segment dimensions, joint constraints and visual fields.

The coordinate reference system used to model the workplace includes global and component axes that can be defined by the system or the user. Several methods of describing the workplace components are possible so that reference points, 2-D surfaces and 3-D shapes can be modelled. The components convey solid versus penetrable and rigid versus deformable characteristics. By defining heirarchial belonging and limits of motion of workplace components, mechanical-movement sequences can be simulated.

3.2. Program Inputs

To accommodate the different approaches that are used by different specialists, on different applications, and having different types of input, several input modes can be employed (e.g. keyboard, cursor, digitizing tablet). When defining the man-model or workplace, a wide variety of input variables are available, in an easy-to-use format. The man-model's input requirements can be satisfied using several different variable-strings that convey internal or external body dimensions, in either metric or imperial units, so that different data sets are compatible. The workplace model can be used to depict actual or conceptual workplace scenarios that are input interactively or from a file. Each component model builds on a data base of stored workplace components.

Consistency checks and error messages are integral to the system, to assure that the man-model reflects realistic human traits (e.g. the summation of internal link formations to reflect external body dimensions). One or more man-models can be generated employing several methods. First, the man-model can be computer-generated with fixed percentiles (e.g. 5th, 50th ,95th) or disproportionate percentiles (e.g. 5th percentile seated height, 70th percentile leg length). Second, the man-model can be generated from the input of either actual or conceptual operator measurements. Once the dimensional characteristics of the man-model have been specified, the desired static posture of the man-model can be selected from several options including: sitting, standing, laying down, crawling, crouching and kneeling. The man-model's posture can then be modified by flexion/extension, adduction/abduction and rotation of the limbs around their joint centres, in incremental or absolute amounts. The man-model can also be positioned to a reference point such as the seat reference point, a desired eye location or a foot anchor point.

Besides specifying isolated limb movements, goal-oriented movements that aim to satisfy reach, vision and body clearance requirements can be initiated. These are based on mathematical algorithms that adhere to the limits previously set on the model's dimensional and visual characteristics.

3.3. Ergonomic Analyses

Operator Reach:

Reach objectives within the workplace can involve one or more targets, using one or more limbs, either sequentially or simultaneously. The hands and feet can be modelled whereby the fingertips, palms, wrists, toes, heels and balls of the feet are represented numerically as the points of contact to the target, provided that the reach excursions are simulated adequately. The reach algorithm is able to incorporate objects such as hand tools (described geometrically) as an extension of the limb performing the reach. The reach target is defined by a single point, a path of points, or by object name. Reach success or failure is indicated where failure is expressed numerically as a resultant distance and limb termination point (i.e. by x-y-z coordinates), or by labelling an obstructing object. The user can instruct the system to automatically reposition the operator, according to pre-prescribed limits, and to attempt the reach sequence once again. In effect, the CAD system is used to optimize the modelled operator's position for reach.

Operator Vision:

The user can complete assessments of vision for an operator's right or left eye, a mid-eye point, or for both eyes. Exploratory assessment of operator vision is accomplished by first assigning the man-model a cone of vision that imposes desired limits (e.g. normal sight characteristics or the envelope described by personal equipment worn on the head). The user then requests a display of the environment from the man-model's view when looking straight ahead or when rotating the eyes up/down and right/left. Using the vision algorithm, the user can specify that the man-model attempt to "see" a visual target that is identified by a point, a series of points or an object name. The target can be inside or outside the man-model's visual field, and viewed in a manner defined by the user (e.g. using specific head and eye movement restrictions). The results indicate success or failure of the attempt, and illustrate objects that impose visual obstructions to the man-model. Vision resulting from reflective surfaces also can be modelled. The user specifies the size, location and focal length of the reflective surface, and instructs that the man-model view the surface. The resulting display indicates the obstruction of the surface to forward vision, as well as the mirror image within the man-model's field of view. Representations of light-sources and shadows contribute to a life-like display of what a real operator would see within the workplace.

Operator Clearance:

When assessing the workplace, potential obstructions to dynamic or static body postures must be identified. Using the body clearance algorithm, the user assigns an acceptance envelope that must be met to ensure adequate room for the operator (e.g. two inches between the operator and overhead surfaces). Any objects that penetrate the envelope are identified by name and location. They can be considered as obstructions based on the depth of envelope penetration, or examined more closely to determine their functional relevance to the operator's comfort, safety and performance. Access and egress procedures for enclosed workplaces can also be examined.

Compliance with Specified Standards:

Many designers employ standards that must be met within their discipline (e.g., US Military Standard 1472C "Human Engineering Design Criteria for Military Systems, Equipment and Facilities"). Anthropometric and workplace design standards can be incorporated in the CAD system's library of data, so that operators and models used in the analysis can be compared for their compliance.

3.4. Program Output

The program output contains general descriptions of the man-model and workplace analysed. The input data used to define the man-model anthropometry and workplace components (by locations and dimensions) are also presented, in tabular form, providing the user with the conditions under which the results of the analyses were obtained. For each of the analyses completed (e.g. reach, vision, body clearance, access/egress and compliance with specified standards) a summary of results states the percentage of operators un-accommodated to the workplace configuration, and why.

The output is available for inspection on a VDU or paper copy, using metric or imperial units of measure. Its format can be modified to include computations of distances between reference points, areas and volumes and can be annotated for presentation in the manner desired by the user.

3.5. Graphics Features

The amount of information that can be provided to the user through graphical display far exceeds that which he will appreciate from alpha-numerical outputs. To exploit this attribute, many viewing options are provided. Front, plan and side views of the workspace are default options: these views can be displayed simultaneously. In addition, the user can command views to any centre of interest from any desired point of view, simulating the effects of moving forward, backward, right, left, up and down. The user can also isolate and magnify areas of interest, displaying the model isometrically, in perspective or in cross-section.

The operator can be modelled as a stick figure representing man's skeletal structure or as an enfleshed figure depicting body volumes provided that the results reflect valid physical characteristics. To appreciate the predicted vision of the operator, vision plots can be displayed using azimuth projections. Representations of workplace components are described using straight lines, curves and arcs that can be drawn using broken, solid or bold lines. The display can be presented as a wire-frame model or with hidden lines removed and using different colours to enhance visual identification of different components.

To change the workplace configuration, a snap-grid can be used to anchor any one component to a desired location. Workplace components can be moved about by designating a location by name, location, or displacement. Any or all components can be temporarily removed from the display by specifying a name, code number or general description. Paramount among the features of the system's graphical output are the capabilities to obtain hard-copy plots during the analyses, in variable sizes, and with an optional header to label or describe the plot.

4. DISCUSSION

Traditional ergonomics tools have lacked an efficient method of representing man in the workplace, but CAD offers a means to develop new aids in man-machine accommodation. The computer graphics permit the construction and manipulation of a 3-dimensional workplace model, while mathematical algorithms describe the dynamic

movements of a man-model. When the models are combined, human performance can be simulated, and ergonomics concepts used to assess working postures, clearances, visual restrictions and the performance of physical tasks. They can be applied to the designs of equipment and work station layouts, controls and displays, accesses, etc. Although few such tools are currently available, their potential justifies their further development.

When determining the man-modelling CAD features to be provided to potential users, the requirements must be appraised according to their skill levels, the types of data they use, the assessments they perform, the applications they address and the stages at which they contribute to the design process. By offering the software options that have been suggested, the majority of users will find the flexibility they require to perform workplace design and evaluation tasks, according to their preferred manner. Therefore, designers who are interested in employing a man-modelling CAD system for workplace design can use the features discussed as criteria for selecting their most appropriate system.

Having determined the man-modelling CAD users' needs, other requirements must be addressed. First, it is advised that the system facilitate general workplace applications so that its use is maximized. Second, the system must be cost-effective, in terms of acquisition and execution. Often, this is influenced by the compatibility of the system's software with in-house computing hardware. Finally, future development of the system must be foreseen. Otherwise, the users run the risk of obtaining software that will quickly become obsolete in view of the rapid advancement of CAD technology. The real test of success for any CAD system will be whether it is actually used for its intended purpose, and is appreciated by its users.

The anthropometric man-models that are presently available within CAD systems remain quite primitive. It is hoped that computer man-models of the future will combine the mathematical algorithms that are currently used in biodynamic analyses with the increasingly sophisticated animation techniques that are being developed. By building upon ergonomics assessment concepts, methods to evaluate the ever-increasing complexity of workplace tasks can be generated. Therefore, now is the time to specify the ergonomic analyses that should be provided using man-modelling CAD, and how they should be presented to the CAD user.

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